

Data Analysis of Strip-Line Board for TOF-PET

Abhinav Prem^{1,2}

¹University of Southern California
Los Angeles, CA

²Fermi National Accelerator Laboratory
Batavia, IL

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- ▶ Brief Introduction to PET Physics
- ▶ Experimental Setup
- ▶ Data Analysis
- ▶ Conclusions
- ▶ References
- ▶ Acknowledgements

First, Some Biology

- ▶ Cancer cells have higher than average rate of glucose metabolism.
- ▶ Certain radiotracers, such as ^{18}F -fluoro-deoxy-glucose (^{18}F -FDG) follow metabolic path similar to glucose.
- ▶ Unlike glucose, tracers don't metabolise to CO_2 and water but remain trapped in tissue.
- ▶ Higher density of tracers near cancerous sites.

- ▶ Positron Emission Tomography (PET) is a radiotracer imaging technique.
- ▶ Patient is injected with radionuclide (^{18}F compounds common in oncology).
- ▶ Trapped radio-tracers decay ($t_{1/2}$ for $^{18}\text{F} = 110$ mins).



- ▶ e^+ annihilates with e^- after travelling $\sim 1\text{mm}$, producing a pair of 511 keV γ .

Coincidences

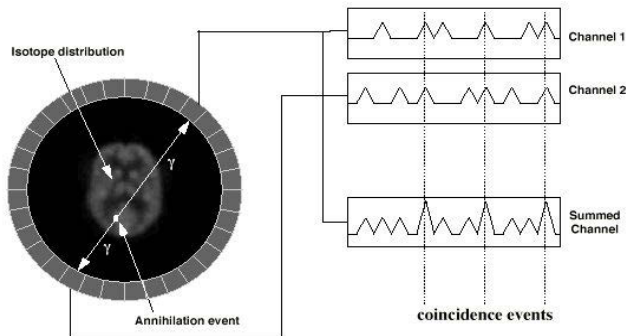
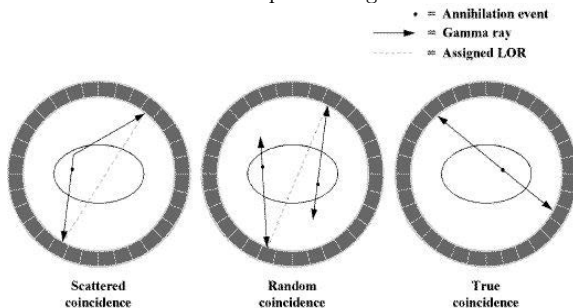


Figure: Coincidence Detection in PET

- ▶ When the photo-detectors placed around patient detect γ , each of them produces a timed pulse.
- ▶ Pulses fed into coincidence circuitry and if two pulses close enough, a coincidence event is recorded.
- ▶ Constrains annihilation event along a line.
- ▶ Spatial resolution of $\sim 10\text{cm}$ attainable with PET technology.

Limitations of Conventional PET

- ▶ In conventional PET, location of individual events is constrained along a line, the Line of Resolution (LOR), and not a point.
- ▶ Not all photons pass through undeviated - scattering, random coincidences, multiple coincidences.
 - ▶ Scattered coincidences - γ undergoes Compton scattering before detection. Event assigned to wrong LOR. Adds statistical noise to signal.
 - ▶ Random coincidences - γ not from same event reach detectors within coincidence window. Also add statistical noise.
 - ▶ Multiple coincidences - More than two γ detected within coincidence window. Causes event mis-positioning.



- ▶ $\sim 15 \text{ mSv}$ is allowed level of radiation exposure for radiation workers at Fermilabs.
- ▶ For adults, exposure from single PET scan $\sim 8 \text{ mSv}$.
- ▶ From PET+CT $\sim 30 \text{ mSv}$.
- ▶ Radiation effects cumulative in nature.
- ▶ Probability of developing oncological complications from a single PET scan on order of 0.1%
- ▶ Use of PET as a diagnostic tool limited.

Advantages of Time of Flight (TOF) PET

- ▶ Can increase resolution by accurately measuring the arrival time of the two 511 keV photons.
- ▶ This constrains the location of the positron to a point rather than a line.
- ▶ If the scanner has a radius x , event is displaced by Δx , speed of light is c , arrival time of photon 1 is T_1 and photon 2 is T_2 , Δt is coincidence timing resolution, Δx is resulting spatial resolution, then:

$$T_1 = \frac{x - \Delta x}{c}, T_2 = \frac{x + \Delta x}{c} \quad (2)$$

$$\Rightarrow \Delta t = T_2 - T_1 = \frac{2 \times \Delta x}{c} \quad (3)$$

$$\Rightarrow \Delta x = \frac{\Delta t \times c}{2} \quad (4)$$

- ▶ For $\Delta t = 200\text{ps}$, spatial resolution of $\sim 3\text{cm}$.

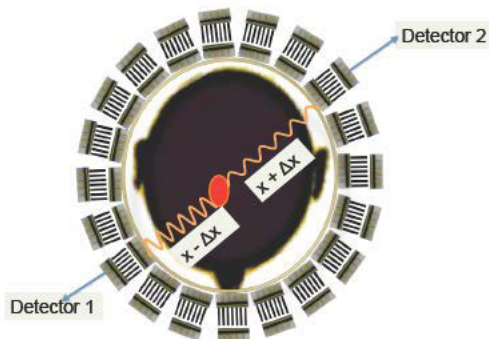
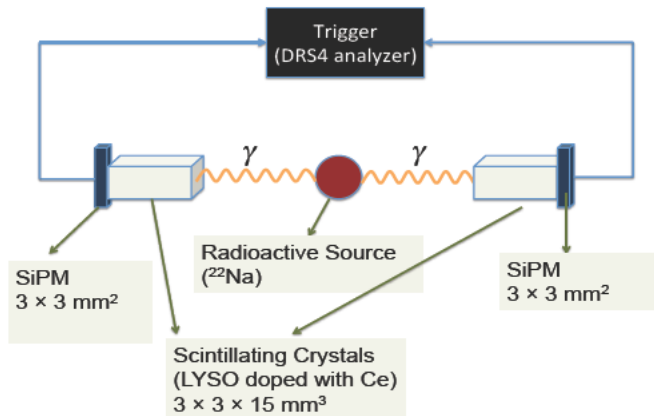


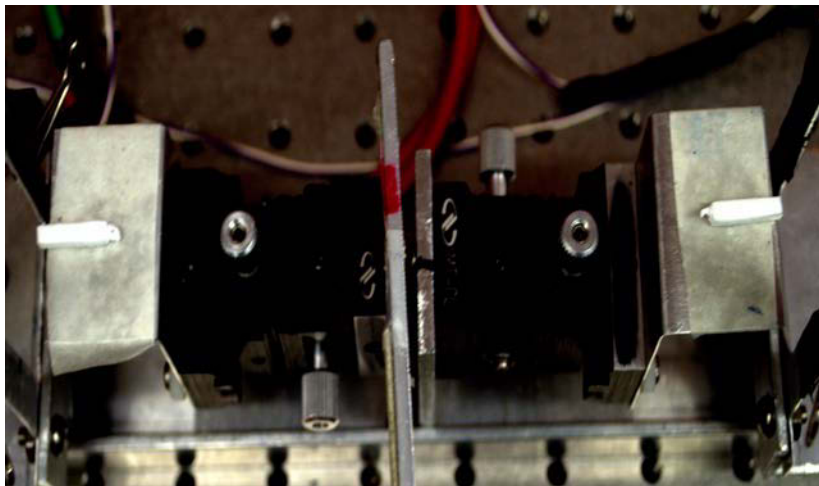
Figure: Coincidence Detection in PET

Basic Layout



- ▶ Radioactive source - ^{22}Na
- ▶ Scintillating Crystals - $3 \times 3 \times 15 \text{ mm}^3$ LYSO crystals doped with Ce and wrapped in Teflon to increase light yield.
- ▶ Silicon Photo Multipliers (SiPMs) - Need less voltage ($\sim 30\text{-}70\text{V}$) than PMTs ($\sim 1000\text{V}$), compact, insensitive to magnetic fields.
- ▶ Electronics - amplifiers, discriminator, trigger circuit, signal processing circuit.

Layout

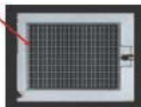


Components



Photodetector Cell

SiPM



Single SiPM



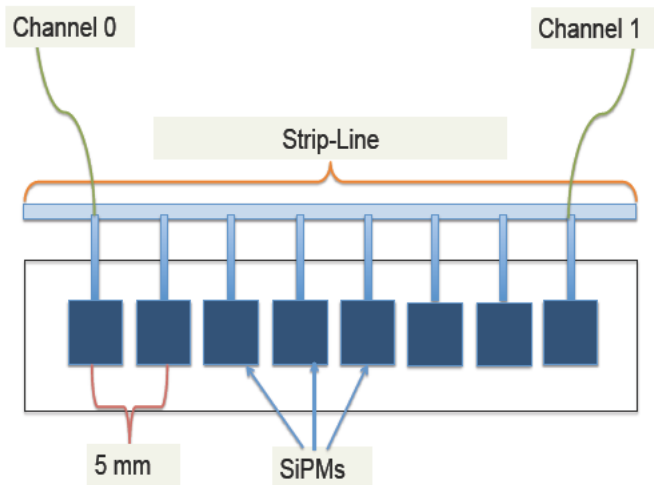
Scintillating Crystal



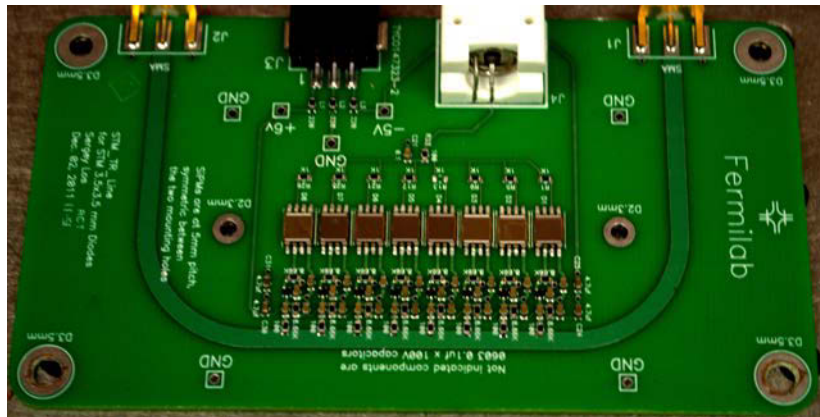
Electronics Front End

Strip-Line Board

- ▶ In a detector, there will be multiple crystals, each with a corresponding SiPM which needs to be read out.
- ▶ So 8 crystals \Rightarrow 8 SiPMs \Rightarrow 8 readout channels. This is cost ineffective.
- ▶ The Strip-Line board is a solution to this. Need only 2 readout channels.



Strip-Line Board



Strip-Line Board: How it works

- ▶ If T_1 is propagation time for Channel 0 pulse, T_2 is propagation time for Channel 1 pulse, c is speed of signal propagation along strip-line, Δt is coincidence timing resolution, Δx is resulting spatial resolution, then:

$$T_1 = \frac{x - \Delta x}{c}, T_2 = \frac{x + \Delta x}{c} \quad (5)$$

$$\Rightarrow \Delta x = \frac{\Delta t \times c}{2} \quad (6)$$

- ▶ If # of crystals hit simultaneously low and Δt small enough, then can determine which SiPM was hit. Cost effective solution.
- ▶ Goal is minimizing Δt

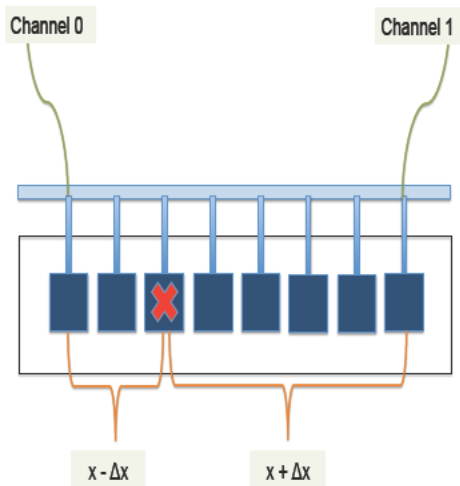


Figure: Determining posⁿ of activated SiPM

Strip-Line Data

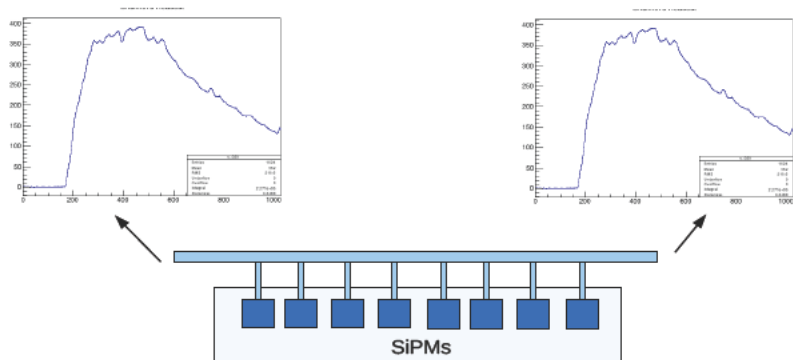


Figure: Strip Line Readout

- ▶ For individual events, pulse shape not distorted as it propagates along strip-line.
- ▶ Pulse shapes only linear in small region.
- ▶ Linear fit procedure can use $\sim 2\text{-}35\%$ part of leading edge, limiting the timing resolution.

Energy Distribution

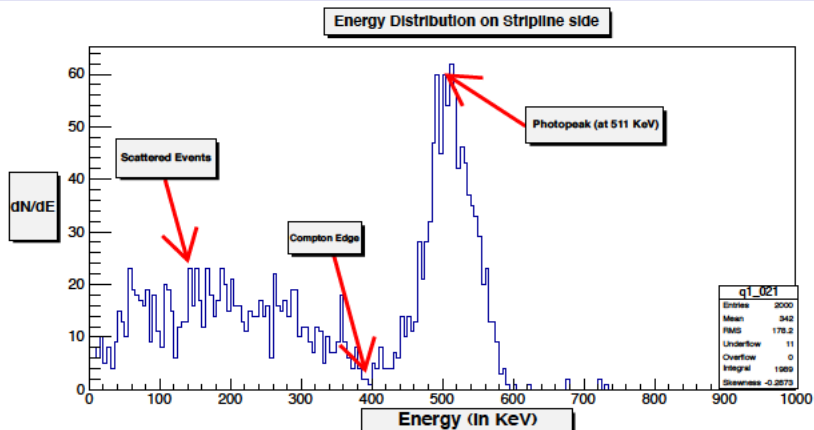


Figure: Energy Distribution

- To measure incident photon energy:
 - Integrate the pulse shape.
 - Normalize the photopeak to 511 keV by introducing calibration constants - one scale factor per channel.

Fitting Procedure

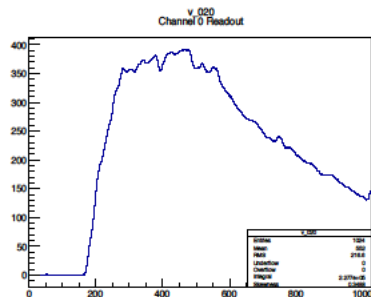


Figure: Channel 0

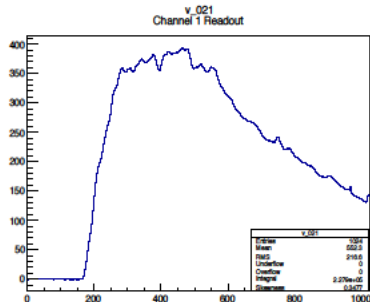
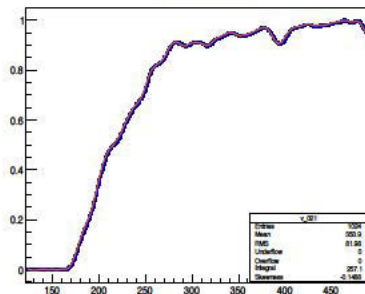


Figure: Channel 1

- ▶ Strip-Line read out from two ends: Ch 0 and Ch 1
- ▶ Pulse shapes readout from diff. channels for single events differ only by horizontal movement.
- ▶ Data driven fitting procedure.
- ▶ No assumptions made about the pulse shape.
- ▶ Utilize $\sim 2\text{-}60\%$ of leading edge for fitting.

Fitting Procedure (contd.)

v_021
Fit Channel 1 with Channel 0



v_021
Zoomed in View

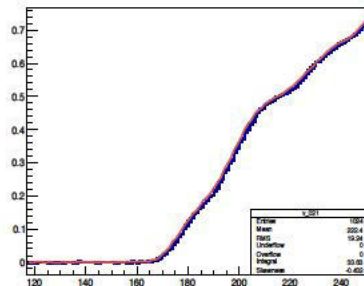


Figure: Fit Ch 1 Readout with Ch 0 Shape

Figure: Zoomed In

- ▶ Normalize both pulses to $V_{max} = 1$.
- ▶ Fit Ch 0 using a local parabolic interpolation.
- ▶ Extract this function and use to fit the readout from Ch 1.
- ▶ Horizontal shift gives us the timing difference across strip-line.

$$\Delta T = T_2 - T_1 \quad (7)$$

- ▶ Timing resolution, Δt , is the jitter in the horizontal offset ΔT
- ▶ Δt comes directly from the fit.

Results: Timing Resolution

Delta(T)[1]
Timing Resolution across Strip Line

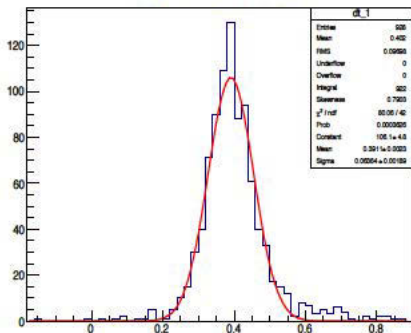


Figure: $\Delta t(\text{Channels})$

Delta(T)[1]
Timing Resolution across Strip Line

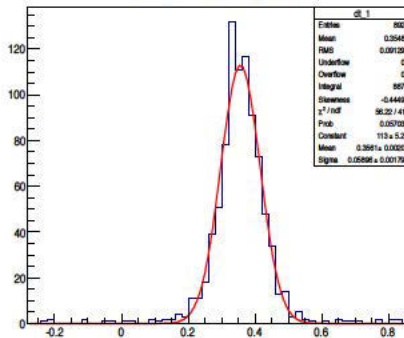


Figure: $\Delta t(\text{Channels})$

- ▶ These are histograms of ΔT from two different SiPMs, where ΔT is given by the horizontal offset.
- ▶ Only events from the photopeak are used in determining the timing resolution.
- ▶ For Figure 1: $\sigma = 0.06364$ (in channels) \Rightarrow FWHM = 30 ps.
- ▶ For Figure 2: $\sigma = 0.05896$ (in channels) \Rightarrow FWHM = 28 ps.
- ▶ FWHM gives Δt .

Results

- ▶ StripLine with 8 SiPM's separated by 5mm
- ▶ Resolution (FWHM) along strip line(in ps):
- ▶ SiPM #1 : 33 ps
- ▶ SiPM #2 : 30 ps
- ▶ SiPM #3 : 28 ps
- ▶ SiPM #4 : 27 ps
- ▶ SiPM #7 : 46 ps
- ▶ SiPM #8 : 33 ps
- ▶ SiPMs #5 & #6 non-functional.
- ▶ Across the stripline (length = 35mm), measure speed of pulse $\sim 0.52c$
- ▶ Using eqⁿ (6), this translates to a spatial resolution of:
 - ▶ ~ 2.1 mm (FWHM)
 - ▶ ~ 1 mm (σ)
- ▶ Since SiPM's separated by 5mm, this resolution allows us to determine with good accuracy which crystal was hit.

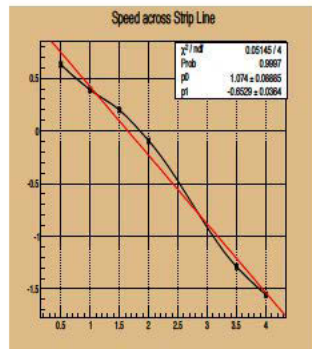


Figure: Δt Peak position (channels) vs SiPM position (in cm)

- ▶ Strip-Line boards provide cost effective method of identifying which crystals detect γ
- ▶ Timing Resolution of 30ps reproducible using described fitting procedure.
- ▶ Corresponds to spatial resolution of ~ 2.1 mm (FWHM).
- ▶ For SiPM pitch of 5mm, this resolution allows us to identify the SiPM on the Strip-Line at a level of $\sigma \sim +/- 2$ mm.

- ▶ Moses, William W. '*Recent Advances and Future Advances in Time-of-Flight PET*'. Nucl Instrum Methods Phys Res A. 2007 October 1. 580(2): 919924.
- ▶ http://depts.washington.edu/nucmed/IRL/pet_intro/index.html

Acknowledgements

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